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TECHNICAL PAPER

Radial superresolution of the two-photon microfabrication method

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Abstract The two-photon microfabrication method, which has been developed over several years, is a new way to produce the real three-dimension microstructure. And now, this technology is recognized as a promising process for the creation of nano- and microscale devices. However, there are still important issues to be settled, one of them is the radial superresolution. The radial superresolution diffraction theory is introduced in the two-photon microfabrication system. This method can improve the radial superresolution of the two-photon microfabrication system. The theoretical analysis of the photosensitive resin is discussed based on the exciting power and concentration of free-radical theory. Experiment results of the two-photon microfabrication method verify the method and show that it can provide weight into the microfabrication system.

1 Introduction

Only several years ago, there appeared a new microfabrication method named two-photon three-dimension (3D) microfabrication method. The technology has some unique

characteristics such as submicron resolution and true 3D fabrication ability, which show great potential advantages on the areas of microstructure, photonic crystals, and MEMS (Micro Electro-Mechanical System) research (Wei et al. 2007; Wei 2008; Liu et al. 2006; Cumpston et al. 1999; Kawata et al. 2001; Jiang et al. 2003).

At present, the most popular two-photon 3D microfabrication method focuses on the polymerization of photosensitive resin. Compared to the single-photon microfabrication methodology, one of the greatest advantages of the two-photon 3D microfabrication methodology is the true 3D fabrication ability. Figure 1 shows the difference between them. In this figure, “a” is the photopolymerization point for the single-photon methodology, and “b” is the photopolymerization point for the two-photon methodology. Obviously, for the single-photon methodology photopolymerization can happen only on the surface of the photosensitive resin, but for the two-photon methodology, photopolymerization can happen both inside and on the surface of the photosensitive resin.

For the two-photon microfabrication system, the resolution power is one of the most important influences on the quality of the fabrication. However, research on the resolution is just beginning. The diffractive optical element proposed in references (Wei et al. 2007; Wei 2008; Jiang 2004; Jiang et al. 2004; Han 2001; Liu et al. 2002; Liu et al. 2003) is used to analyze the radial superresolution of the two-photon microfabrication system in this article. The experiments are carried out to prove the validity of the diffractive optical element.

2 Theoretical analysis of the radial superresolution of the two-photon microfabrication method

The free-radical photopolymer is composed of photoinitiators, a photosensitizer, and monomers. Photopolymerization

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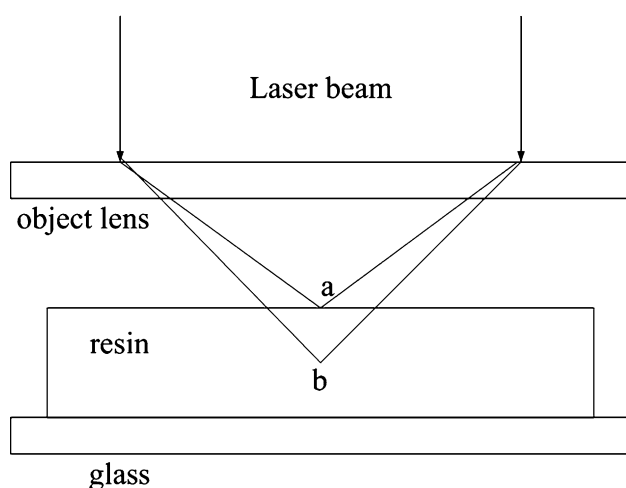


Fig. 1 Comparison between single-photon and two-photon methods of microfabrication method

is usually concerned with the creation of a polymer through a chain reaction initiated by laser, and it consists of three basic processes: a radical reaction, a monomer radical reaction, and polymerization termination. According to the principle of two-photon absorption, an initiator is excited from the ground to the excited states by absorbing two photons simultaneously and the single-photon absorption is very weak. After the free-radical photopolymer is produced, the polymerization process depends on the concentration of the radicals and the efficiency of the polymerization reaction.

With certain conditions, the polymerization process will take place. In this process, the concentration of the radical photopolymer ξ reaches the polymerization critical value ξ_{th} . But nothing will happen if $\xi < \xi_{th}$. For the photosensitive resin given, the polymerization critical value is constant. So the resolution of the two-photon microfabrication system could be obtained from the concentration of the radical photopolymer. As the concentration of the radical photopolymer ξ is the ratio to the intensity of the laser, the radial superresolution of the two-photon microfabrication method is achieved by adjusting the amplitude or phase of the incident laser wavefront when the laser power and the time of the exposure are constant.

And under certain conditions, the ratio between the intensity of the laser I and the concentration of the radical photopolymer ξ is definite. So, the intensity critical value I_{th} could be used to define the radial superresolution of the two-photon microfabrication method, just as the polymerization critical value ξ_{th} could. That is, under certain conditions, the polymerization will take place where the intensity of the laser $I \geq I_{th}$, but nothing will happen if $I < I_{th}$. And after the laser's characteristics and the fabrication exposure time is set, the intensity critical value I_{th} of the photosensitive resin is constant.

In a word, the radial superresolution of the two-photon microfabrication method could be achieved by the intensity distribution of the laser I , and the intensity distribution of the laser I could be achieved by the diffractive superresolution element (DSE), which is specially designed. So the radial superresolution of the two-photon microfabrication method could be achieved by specially designed DSE.

3 Design of the radial diffractive superresolution element

3.1 The structure of the two-photon microfabrication system

Figure 2 describes the principle of the two-photon microfabrication system. In this system, there are four subsystems.

The first subsystem is the femto-second laser—the Ti:Sapphire laser of the TIGER corporation, its highest output power is 1.2 W, the laser's pulse width is more than 40 fs, and the laser's wave length range is 700–900 nm, the highest output power of a single pulse is less than 10 nJ. During the two-photon microfabrication period the output power is <400 mW, the center wave length is 740 nm, the pulse width is 160 fs, and the repetitive frequency is 50 MHz.

The second subsystem is the confocal microscope—BX51WI of the Olympus Corporation. It contains a CCD, which is connected to a computer. The original platform is replaced by 3D platform, which is produced by the PI Corporation. During the two-photon microfabrication process only the bottom lighting lamp is available because of the S-3 resin's character that the refractive index of the

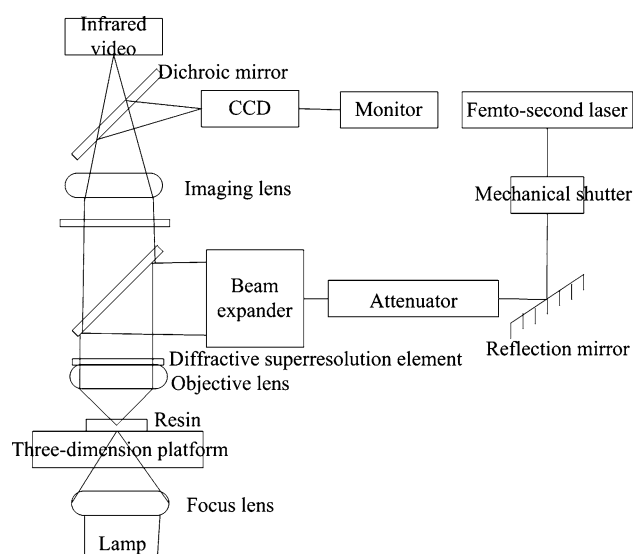


Fig. 2 Block diagram of two-photon microfabrication system

solidified resin changes little. And above all the DSE is set next to the objective lens.

The third subsystem is the expose and control system. The computer is used to control the shutter and the 3D platform together to get the exact expose time and fabricate the 3D microstructure.

The fourth part contains some optical device, such as the attenuator, the expander and so on.

Compared with other two-photon microfabrication systems, the radial DSE is introduced into the system, which make it possible for the optimization of the radial distribution intensity on the area of the point spread function (PSF). The laser beam from the femtosecond laser device passes the shutter, the attenuator, and the expander sequentially and becomes a plane wave. Then the plane wave passes the DSE and the objective lens continuously and focuses on the photosensitive resin. The radial DSE in the article is designed as the adjusting amplitude element because it is cheaper than the adjusting phase element and easier to get.

3.2 Introduction of the radial optical diffractive superresolution element

To adjust the intensity of the laser on some special area, a radial superresolution diffractive optical element is necessary. Using the traditional imaging pattern showed in Figs. 2 and 3 describes the performance of the radial optical superresolution pattern.

And according to the Fig. 3, the following can be shown.

1. Strehl ratio S : $S = I_S/I_L$, in which I_S is the center intensity of the superresolution PSF and I_L the center intensity of the traditional diffractive limit of the Airy disk pattern.
2. The size of the main lobe along the radial coordinate G , $G = r_S/r_L$, in which r_S is the radius of the main

lobe's zero point for the superresolution pattern, and r_L is the corresponding radius for the diffractive limit of the Airy disk pattern.

3. The maximum intensity of the side lobe along the radial coordinate M , $M = I_M/I_S$, in which I_M is the maximum intensity of the side lobe along the radial coordinate of the superresolution pattern.

According to the Fresnel approximation, the PSF, which is adjusted by the radial DSE, is

$$I(r_2) = \left(\frac{2\pi}{\lambda f} \right)^2 \left| \int_0^R u(r_1) J_0 \left(\frac{2\pi r_1 r_2}{\lambda f} \right) r_1 dr_1 \right|^2 \quad (1)$$

where r_1 is the radial coordinate on the DSE plane, r_2 the radial coordinate of the PSF area, $u(r_1)$ the DSE transmittance function, λ the wavelength, f the focal length of the object lens, R the radius of the DSE, and J_0 the zero-order Bessel function.

$\rho = r_1/R$ is the radial normalized coordinate in the DSE plane, $\eta = r_2/(0.61\lambda/\text{NA})$ is radial normalized coordinate in the PSF area, $\text{NA} = R/f$. Therefore, the normalized form of Eq. 1 is

$$I(\eta) = 4 \left| \int_0^1 U(\rho) J_0(x_j \eta \rho) \rho d\rho \right|^2 \quad (2)$$

where $U(\rho) = u(r_1)$, $x_j = 3.8317$.

The design of radial DSE with restricted conditions is depicted as a problem of

$$\min_{U(\rho)} G \quad (3a)$$

such that

$$S \geq S_l, M \leq M_u \quad (3b)$$

$$|U(\rho)| \leq 1 \quad (3c)$$

where S_l is the lower bound of the S , M_u is the upper bound of the M .

By means of the global optimal algorithm such as the Genetic algorithm or the Simulated-annealing algorithm (Liu 2004; Strayer 1989; Xing and Xie 1999), Eqs. 3, 3, and 3 can get the optimal answer. And finally the DSE could be got.

3.3 Design of the radial optical diffractive superresolution element

Based on the Eqs. 3, 3, and 3 and the optimal algorithm, the adjusting amplitude radial optical DSE could be got.

Figure 4 shows the structure of the adjusting amplitude radial optical DSE, and Fig. 4a is the planform of the DSE, Fig. 4b is the section of the DSE along the semidiameter. From Fig. 4, it can be seen that the DSE is ring shaped, and the opacity ring is covered by the chrome membrane. The base of the DSE is the transparent quartz glass.

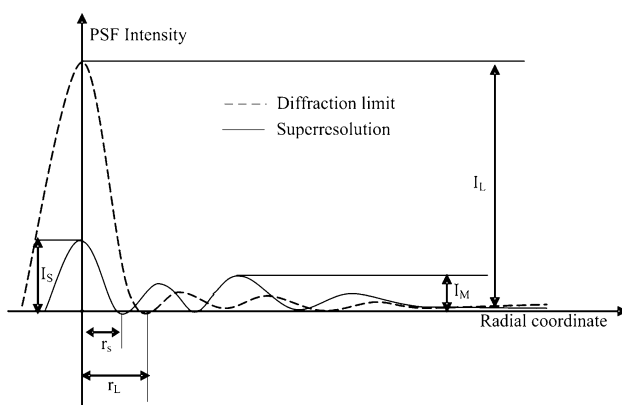
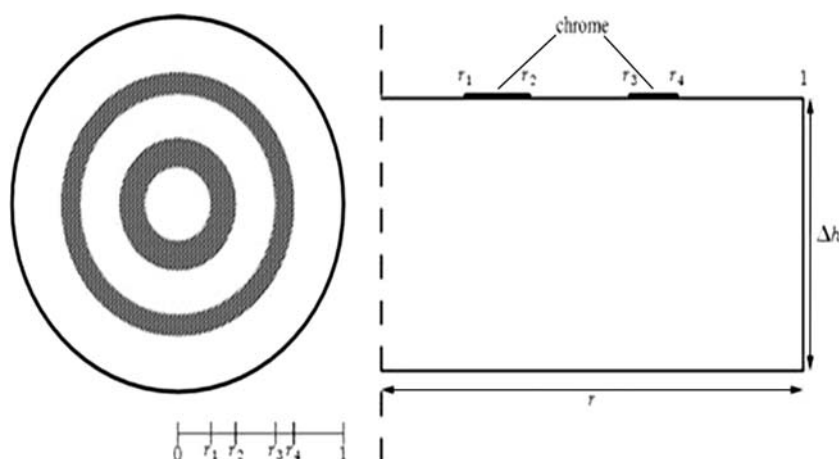


Fig. 3 Performance of radial coordinate

Fig. 4 Structure of the adjusting amplitude radial optical DSE: **a** the planform and **b** the section



For convenience, three adjusting amplitude radial optical DSE are made, and the diameter of each DSE is 5 mm, the character of the DSE is showed in Table 1.

4 Experiment

The radial DSE, which is set in the two-photon microfabrication system, is showed in Fig. 2. And to show the superresolution of the two-photon microfabrication system, the hanging-line microfabrication experiment is designed.

The hanging-line experiment is showed in Fig. 5. First, two erection walls are fabricated, and the distance between them is 5 μm . Then, the lines are fabricated between them with the two-photon microfabrication system. And finally taking advantage of the electron microscope, the super-resolution of the two-photon microfabrication method is showed by the lines.

Figure 6 shows the superresolution of the two-photon microfabrication system, in which the radial superresolution of the line is showed by Fig. 6a, and the axial super-resolution of the line is showed by Fig. 6b.

To get the minimum radial superresolution of the line in the two-photon microfabrication method, the objective lens is immersion lens ($\text{NA} = 1.3$, $n = 1.516$). And as the adjusting amplitude DSE can cause some energy loss, the laser output power is 60–90 mW. Finally, the minimum radial superresolution with the DSE is got and showed in Fig. 7.

During the experiment period, it is found that the repetition of the result is not so good. Even keeping the same experiment condition, the radial superresolution may be different. That may be result from the following reason: (1) the laser power distribution is not in ideal state; (2) the system condition is not stable, such as the expose time, the measure method and so on; (3) the laser output power may fluctuate at 5%.

Table 1 Character of the radial DSE of two-photon microfabrication method

DSE number	Radial normalized coordinate in the DSE plane G								G
	r_1	r_2	r_3	r_4	r_5	r_6	r_7	r_8	
1	0.09	0.49	0.52	0.67					1.199
2	0.09	0.57	0.61	0.65	0.69	0.73			1.203
3	0.01	0.07	0.09	0.19	0.21	0.46	0.49	0.65	1.201

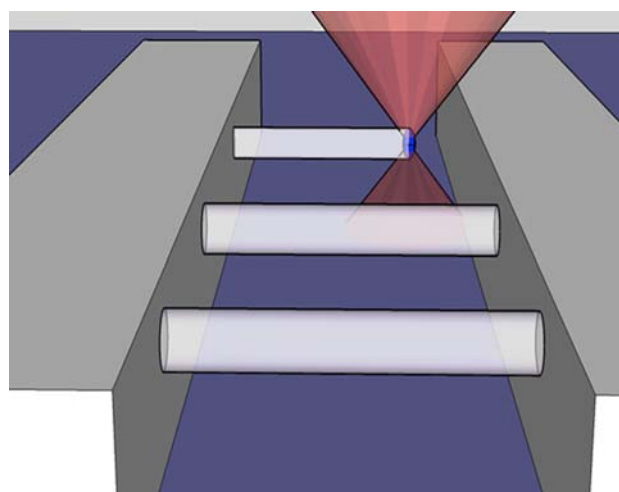


Fig. 5 Hanging-line experiment of the two-photon microfabrication method

But we can still get something from experiment results. After using the DSE, it is easier to get the radial super-resolution line below 100 nm. And above all, we get the minimum superresolution line whose radial superresolution is below 50 nm, which is not available before using the DSE. So, the radial superresolution of the two-photon microfabrication method can be improved by the DSE.

Fig. 6 Hanging line experiment result of the two-photon microfabrication method: **a** planform and **b** side view

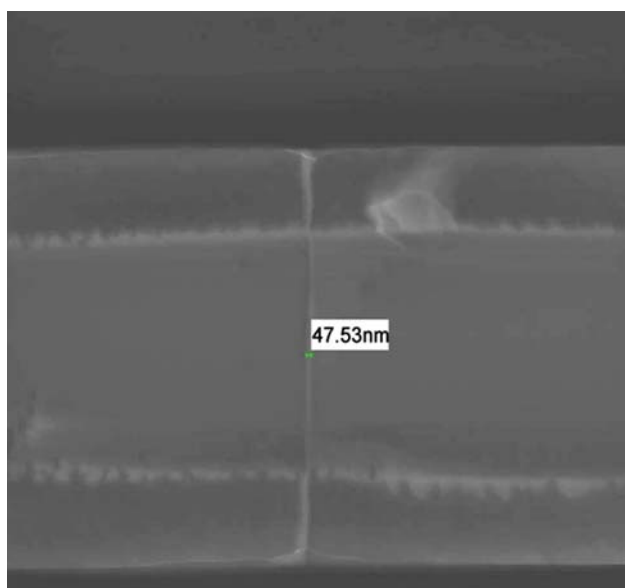
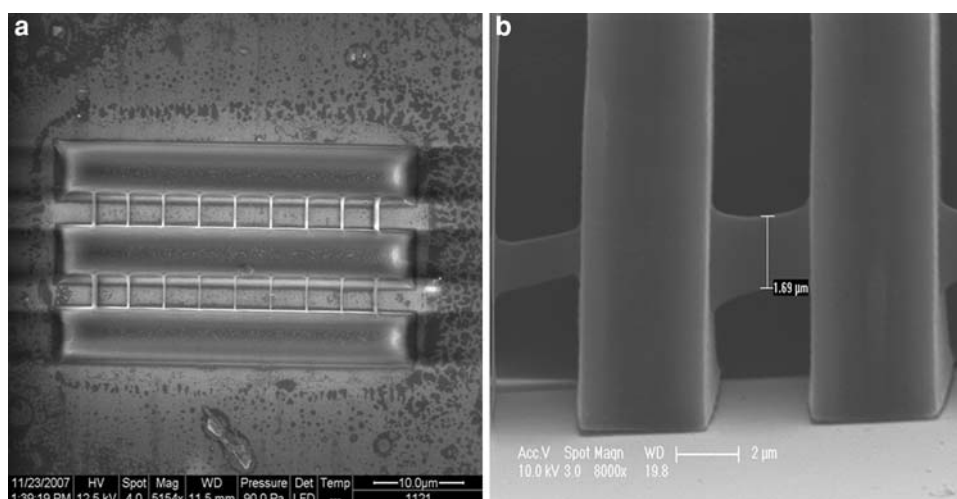


Fig. 7 The minimum superresolution line by using the optical DSE

5 Conclusions

For the two-photon microfabrication system, the radial superresolution can be improved by a properly designed DSE. Therefore, the DSE method provides some references for the application and the theoretical analysis of the radial superresolution of the two-photon microfabrication system. The DSE also increases the cost of the whole system.

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